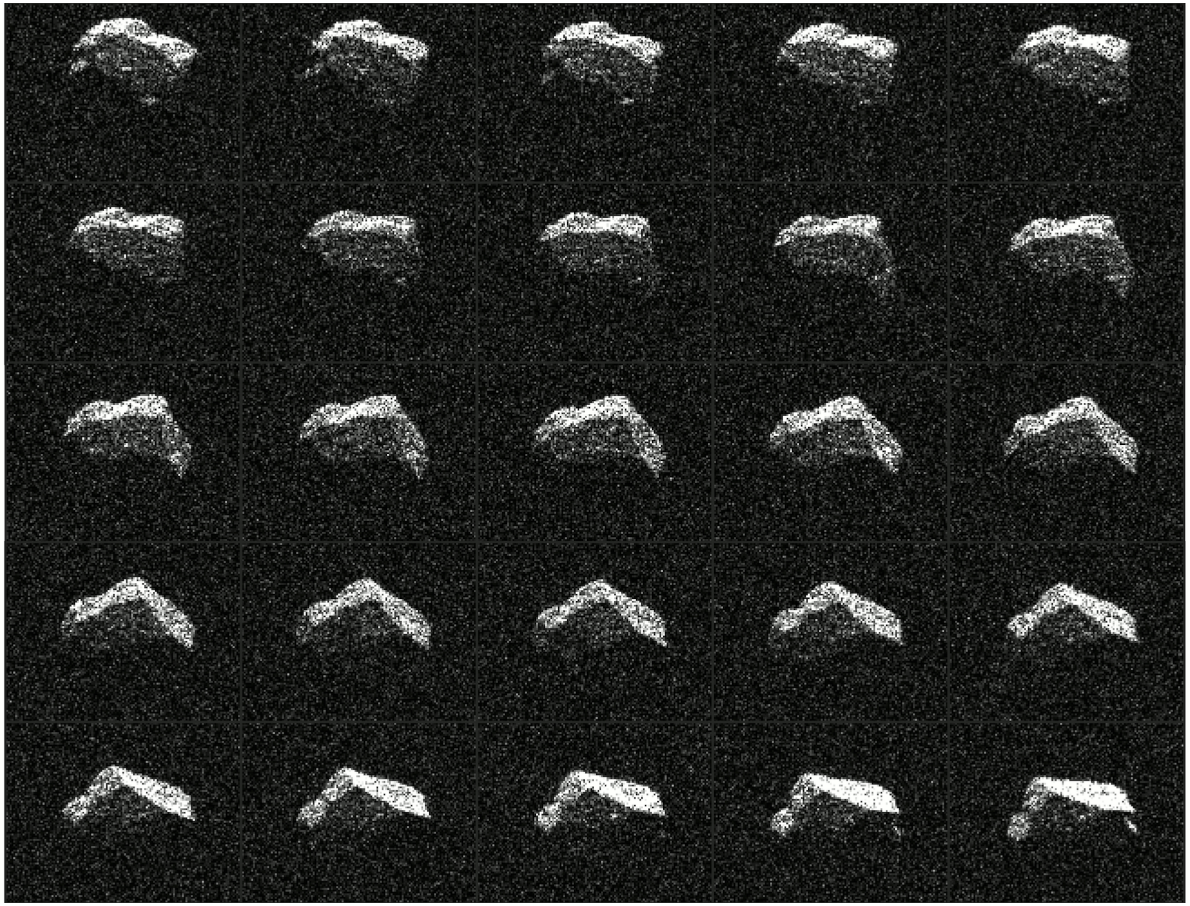


Radar Astronomy

Sardinia Seminar Series

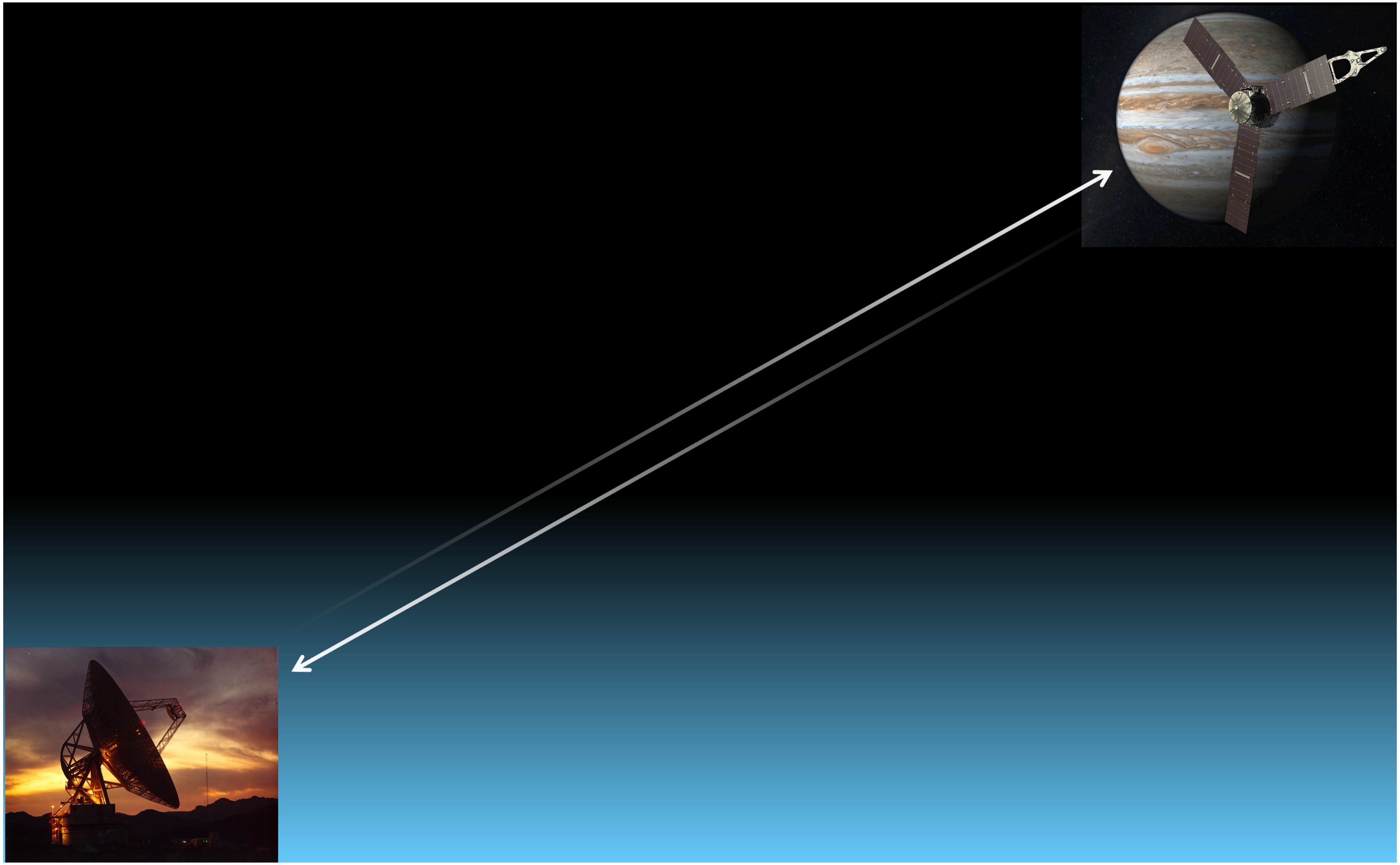
Joseph Lazio

Thanks to L. Benner, M. Brozovic, J. Giorgini, S. Naidu, R. Preston

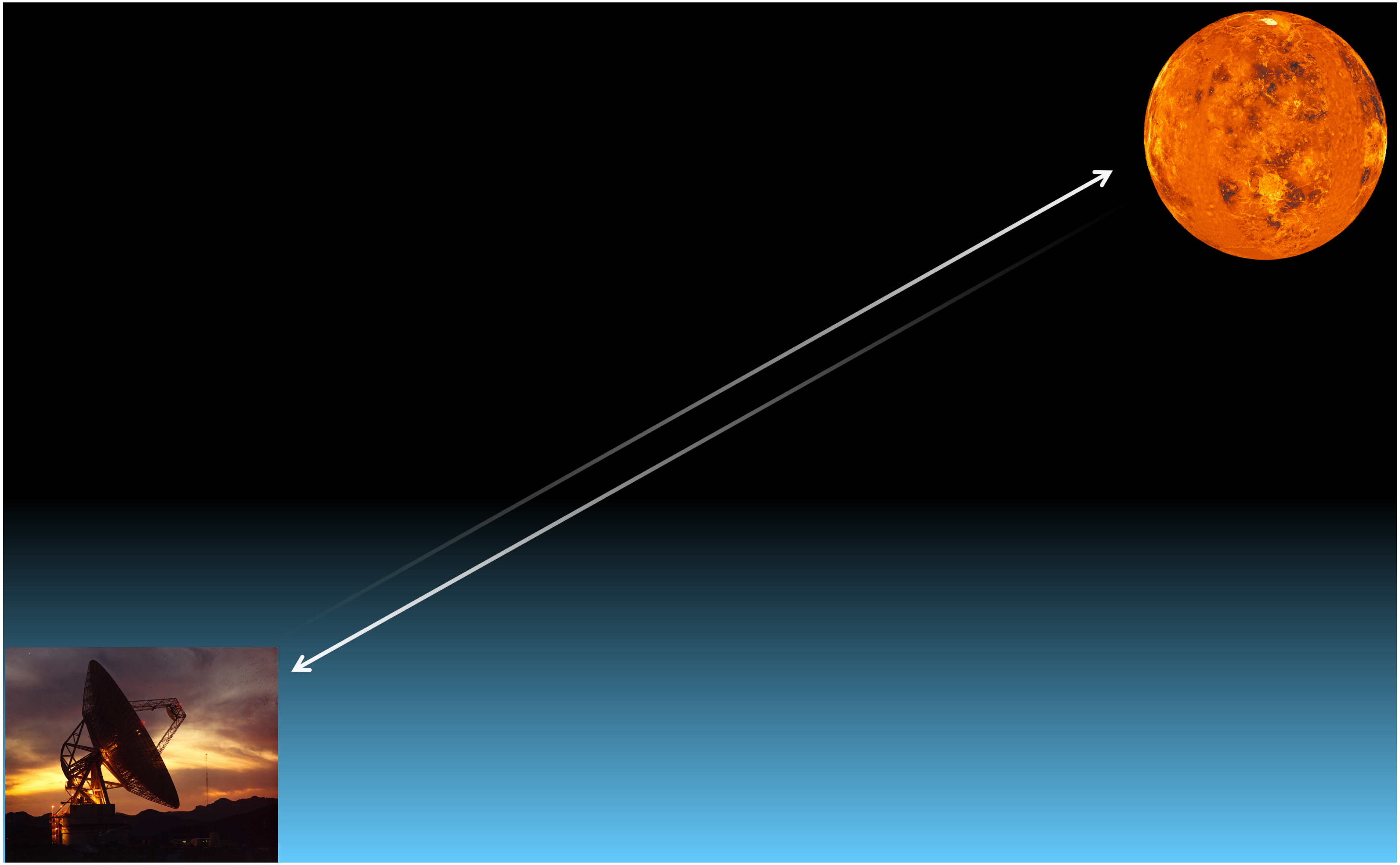
Jet Propulsion Laboratory, California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Spacecraft Telemetry, Tracking, & Command

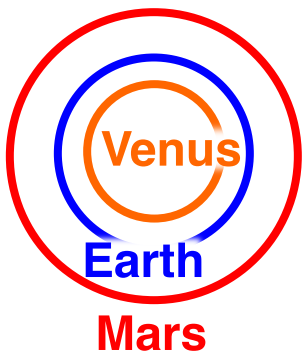


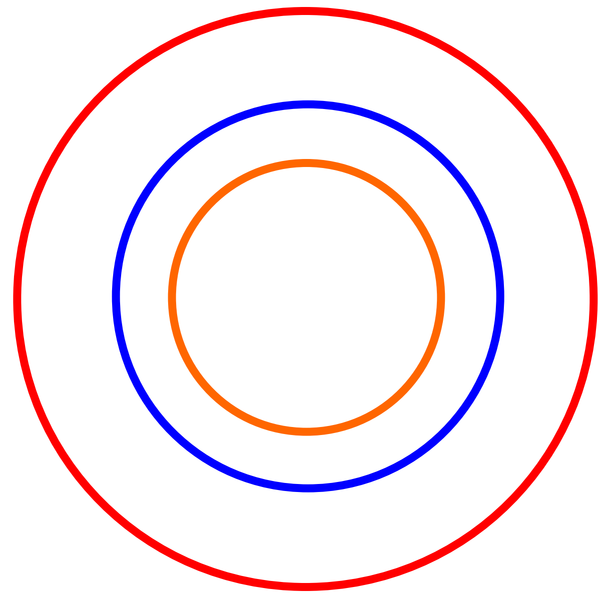
Planetary Radar



Scale of the Solar System

Relative sizes of planetary orbits known for centuries





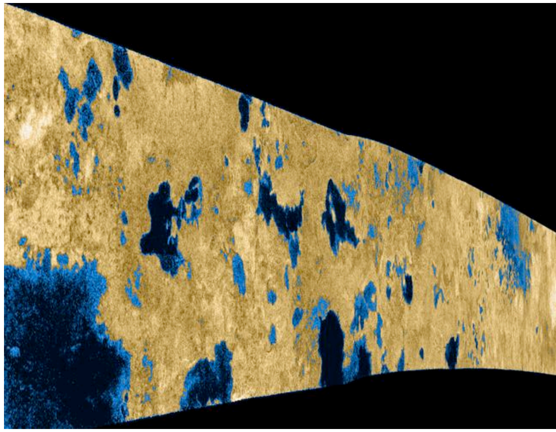
Radar provided absolute sizes of planetary orbits at precision needed for interplanetary navigation

- **Precision measurements from DSIF [DSN] radar measurements**
- **Reduced uncertainty to about 400 km (~ 0.0003%)**

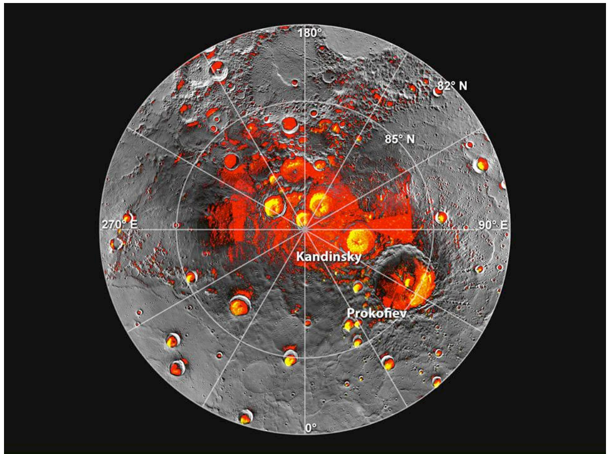
DSN Radar Accomplishments

- **Discovered Venus retrograde rotation (1962)**
- **Probing the surfaces of asteroids (1976)**
- **First radar returns from Titan (1989-1993), suggestive of icy surface but with potential liquids**
- **Anomalous reflections from Mercury (1991), indicative of polar ice**

Magellan **radar image of Venus (NASA/Caltech/JPL)**



Cassini **radar image of Titan (NASA/JPL/USGS)**



MESSENGER+radar image of Mercury (NASA/HU APL/CIW/NAIC)

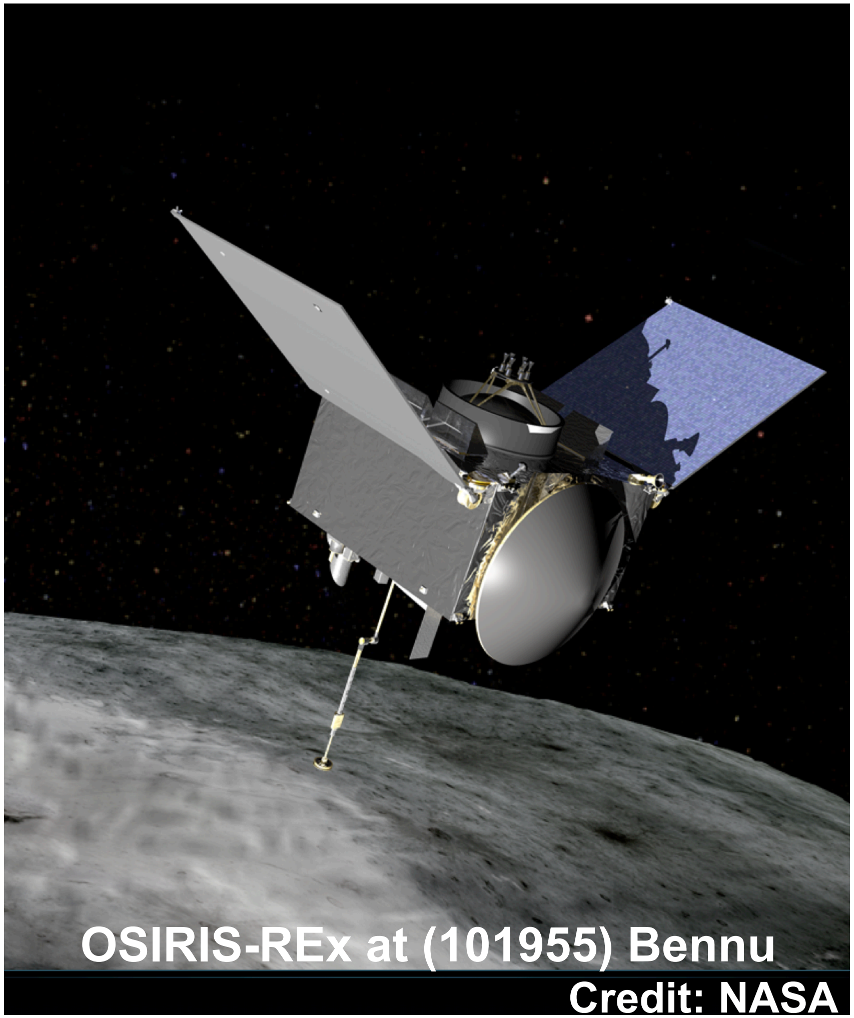
Goldstone Solar System Radar

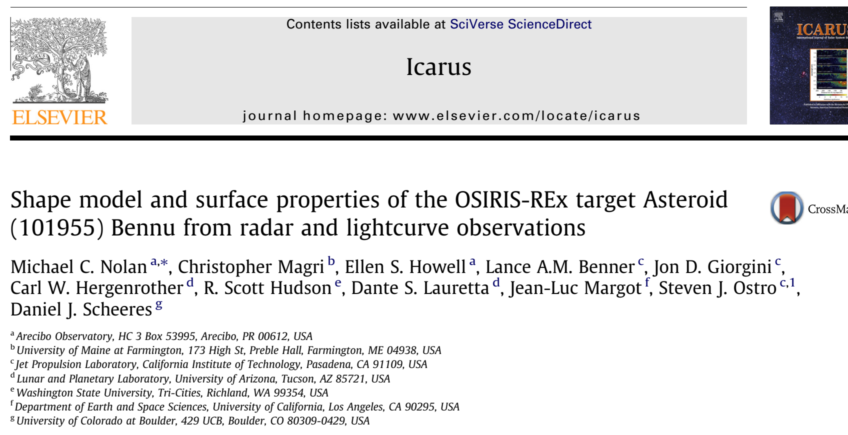
Imaging of Near-Earth Asteroids

Radar delivers size, rotation, shape, density, surface features, precise orbit, non-gravitational forces, presence of satellites, mass, …

- **Robotic or crewed missions: Navigation, orbit planning, and observations**
- **Planetary defense: Orbit determination for hazard assessment**
- **Science: Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere**

Radar Contributions to Space Missions





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journal homepage: www.elsevier.com/locate/icarus

Shape model and surface properties of the OSIRIS-REx target Asteroid (101955) Bennu from radar and lightcurve observations

Michael C. Nolan [a,*], Christopher Magri [b], Ellen S. Howell [a], Lance A.M. Benner [c], Jon D. Giorgini [c], Carl W. Hergenrother [d], R. Scott Hudson [e], Dante S. Lauretta [d], Jean-Luc Margot [f], Steven J. Ostro [c,1], Daniel J. Scheeres [g]

[a] Arecibo Observatory, HC 3 Box 53995, Arecibo, PR 00612, USA
[b] University of Maine at Farmington, 173 High St, Preble Hall, Farmington, ME 04938, USA
[c] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[d] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[e] Washington State University, Tri-Cities, Richland, WA 99354, USA
[f] Department of Earth and Space Sciences, University of California, Los Angeles, CA 90295, USA
[g] University of Colorado at Boulder, 429 UCB, Boulder, CO 80309-0429, USA

International Radar Assets

Goldstone DSS-14 (DSN)
70 m antenna, 450 kW transmitter, 4 cm wavelength (X band)

Arecibo (NAIC)
300 m antenna, 900 kW transmitter, 13 cm wavelength (S band)

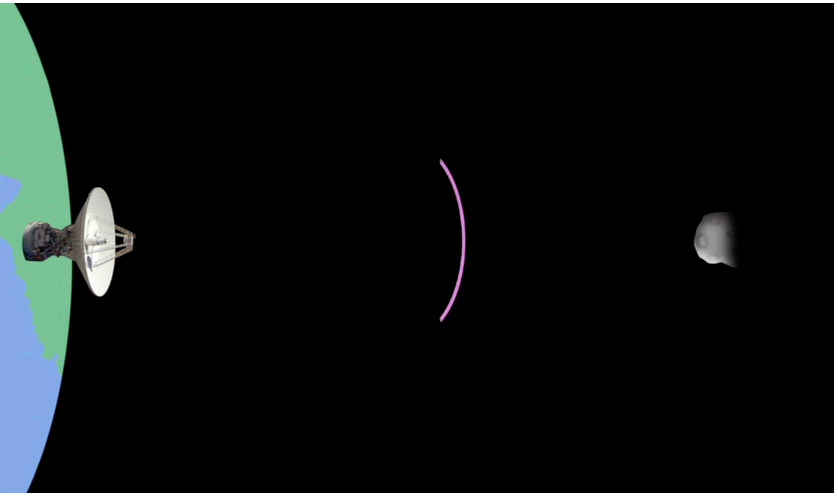
Green Bank Telescope (GBO)
100 m antenna, no transmitter

Canberra DSS-43 (DSN)
70 m antenna, 20 kW transmitter, 4 cm wavelength (X band)
+ Australia Telescope Compact Array

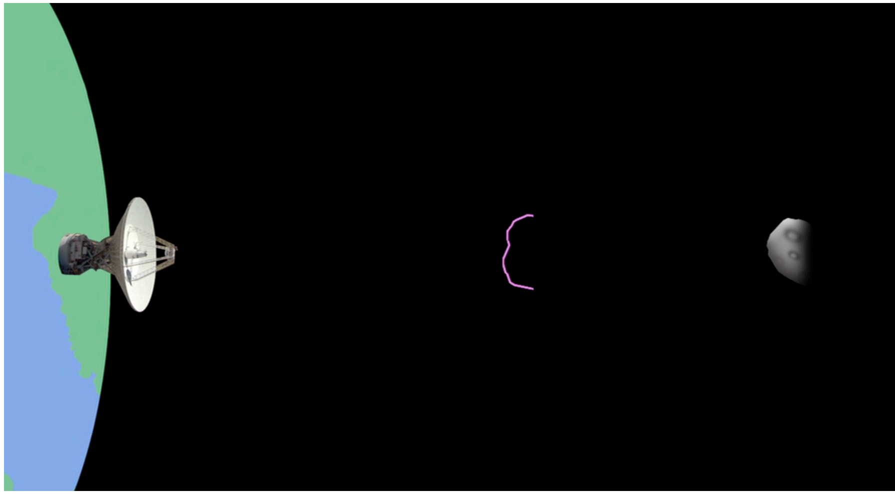
+

Radar Equation

… Tyranny of



Radar transmitter transmits toward target …

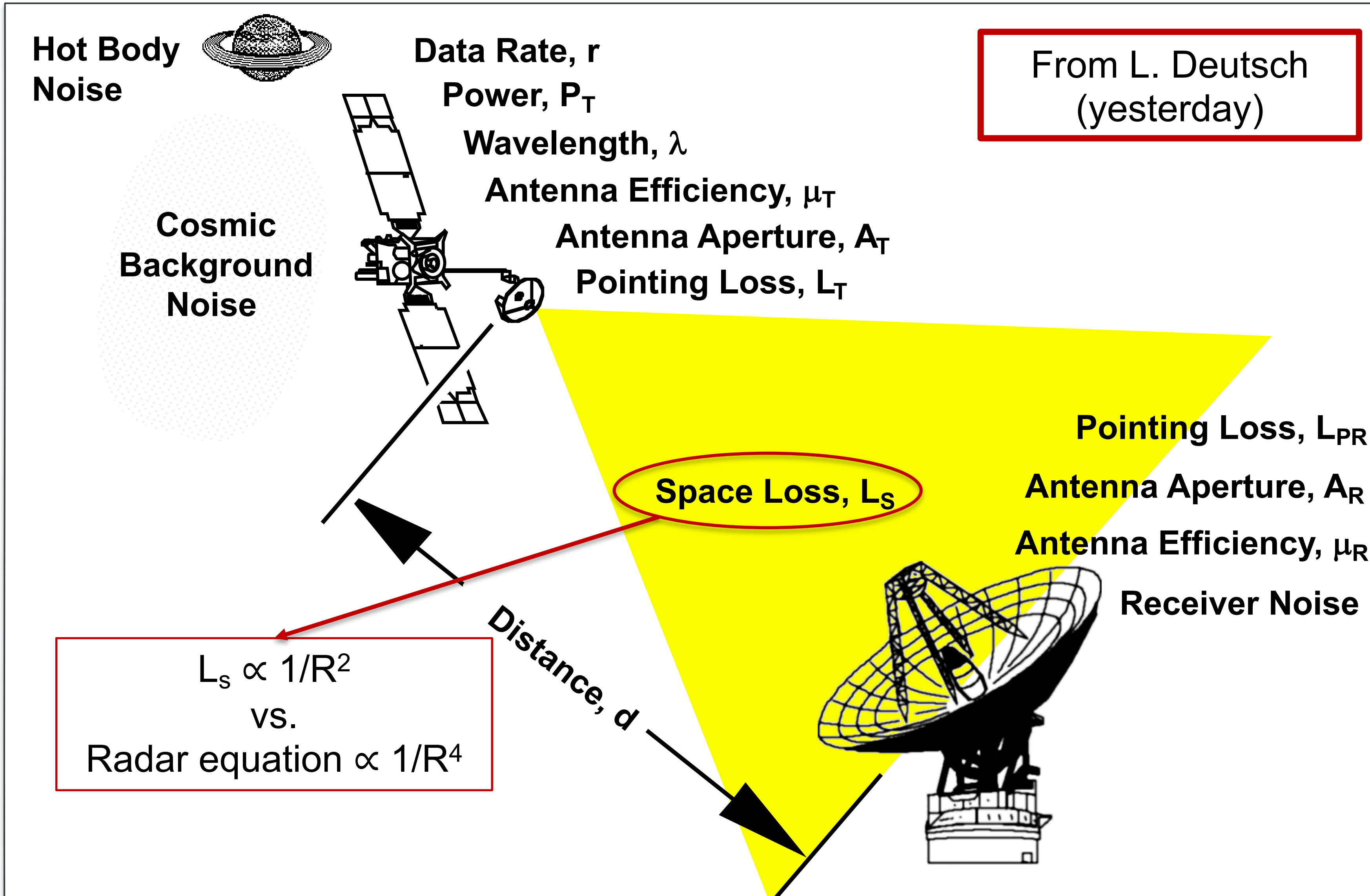


Target reflects, a.k.a. re-transmits, radar signal.

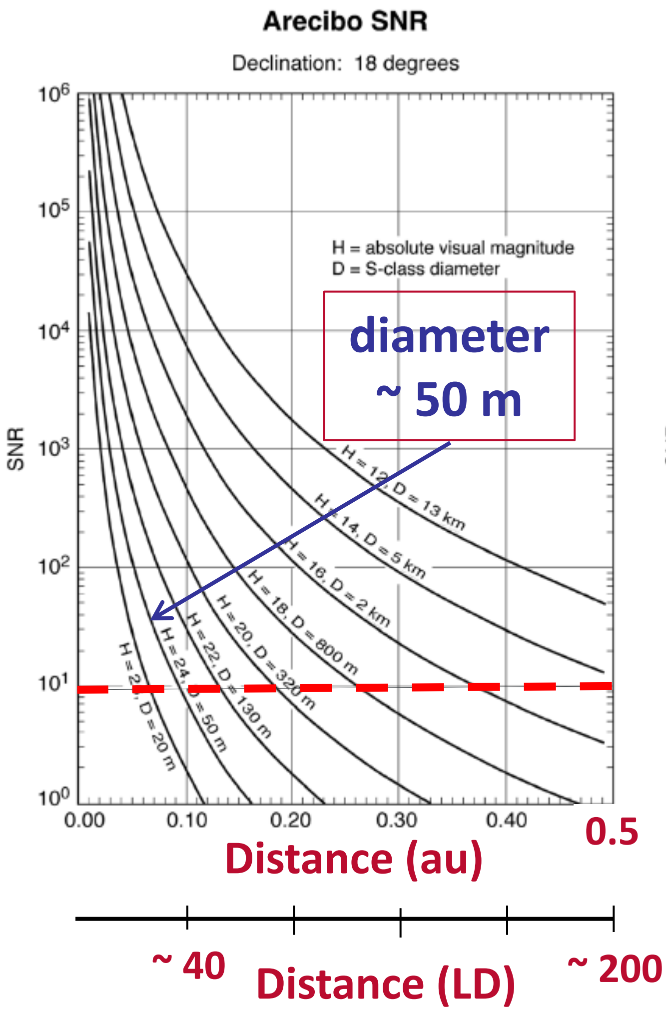
$$P_{\mathrm{RX}} = P_{\mathrm{TX}} \frac{GA\sigma}{(4\pi)^2 R^4}$$

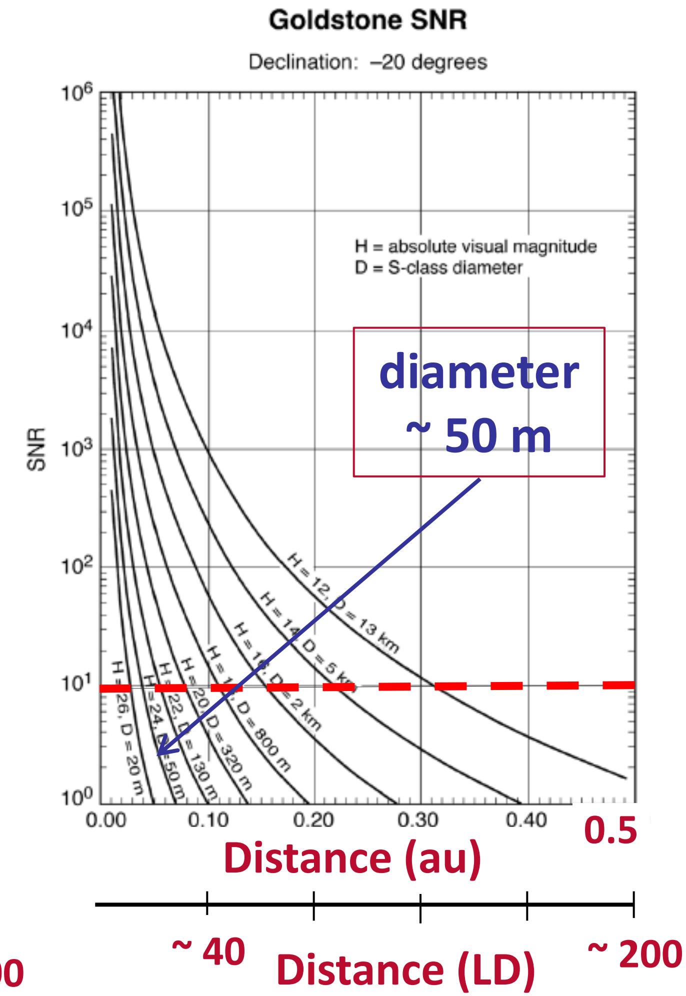
- P_{RX} – received power
- P_{TX} – transmitted power
- G – antenna gain
- A – antenna area
- σ – radar cross-section
- R – range

Radar vs. Deep Space Communications



Radar and NEO Detectability





Ostro & Giorgini

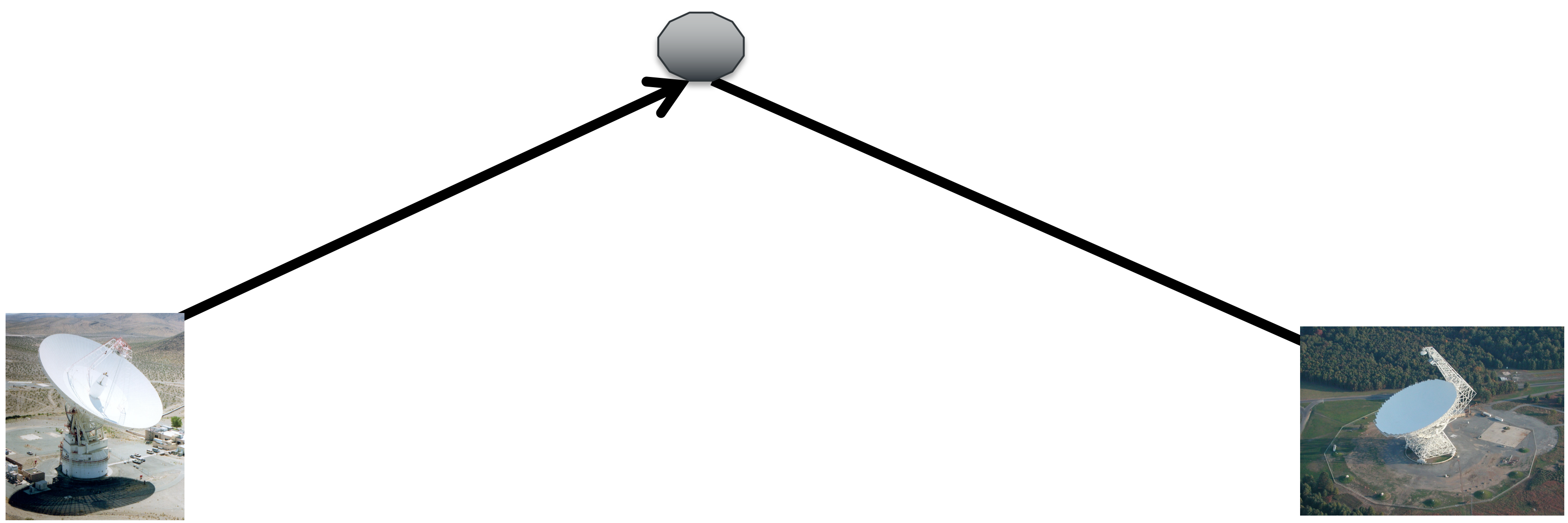
Bistatic Radar Observations

$$\boxed{P_{\mathrm{RX}} = P_{\mathrm{TX}} \frac{GA\sigma}{(4\pi)^2 R^4}}$$

P_{RX} – received power
P_{TX} – transmitted power

P_{RX} = small
P_{TX} = BIG (>~ 500 kW)

Difficult to receive at same antenna, particularly if round-trip light travel time is small



Bistatic Radar Observations

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} \frac{GA\sigma}{(4\pi)^2 R^4}$$

P_{RX} – received power = small
P_{TX} – transmitted power = BIG

Transmit antenna

DSS-14 (Goldstone)

Arecibo (Puerto Rico)

DSS-43 (Tidbinbilla)

Receive antenna

Green Bank Telescope (GBT)
(West Virginia)

Arecibo

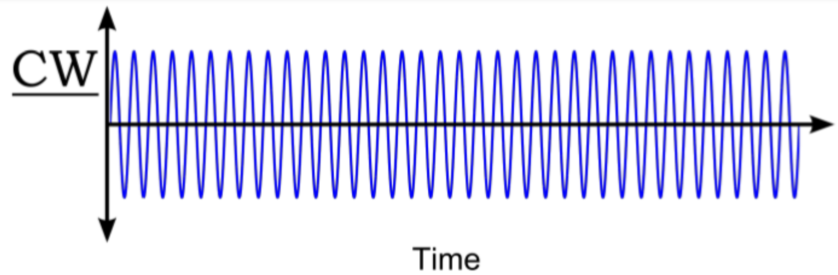
DSS-13 (Goldstone)

Australia Telescope Compact Array (Narrabri, Australia)

Radar Signal Processing

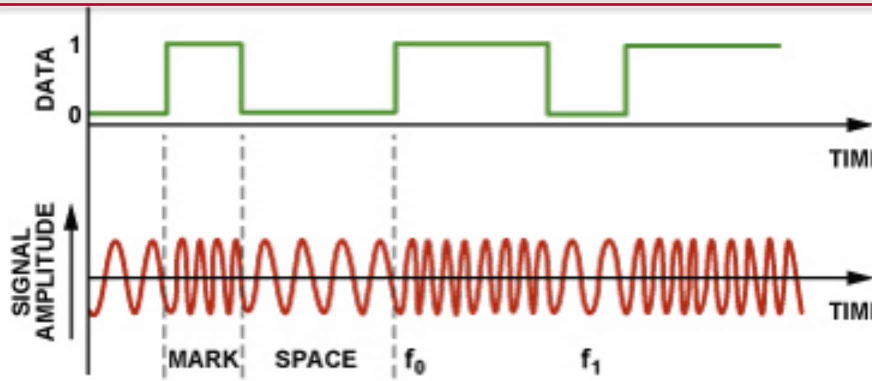
Continuous Wave

Circularly polarized radio wave with constant amplitude and frequency



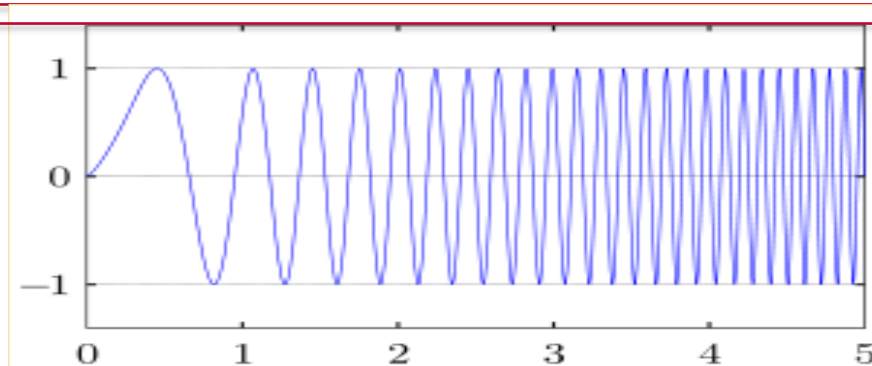
Binary Phase Coding (BPC)

Time-encode waveform



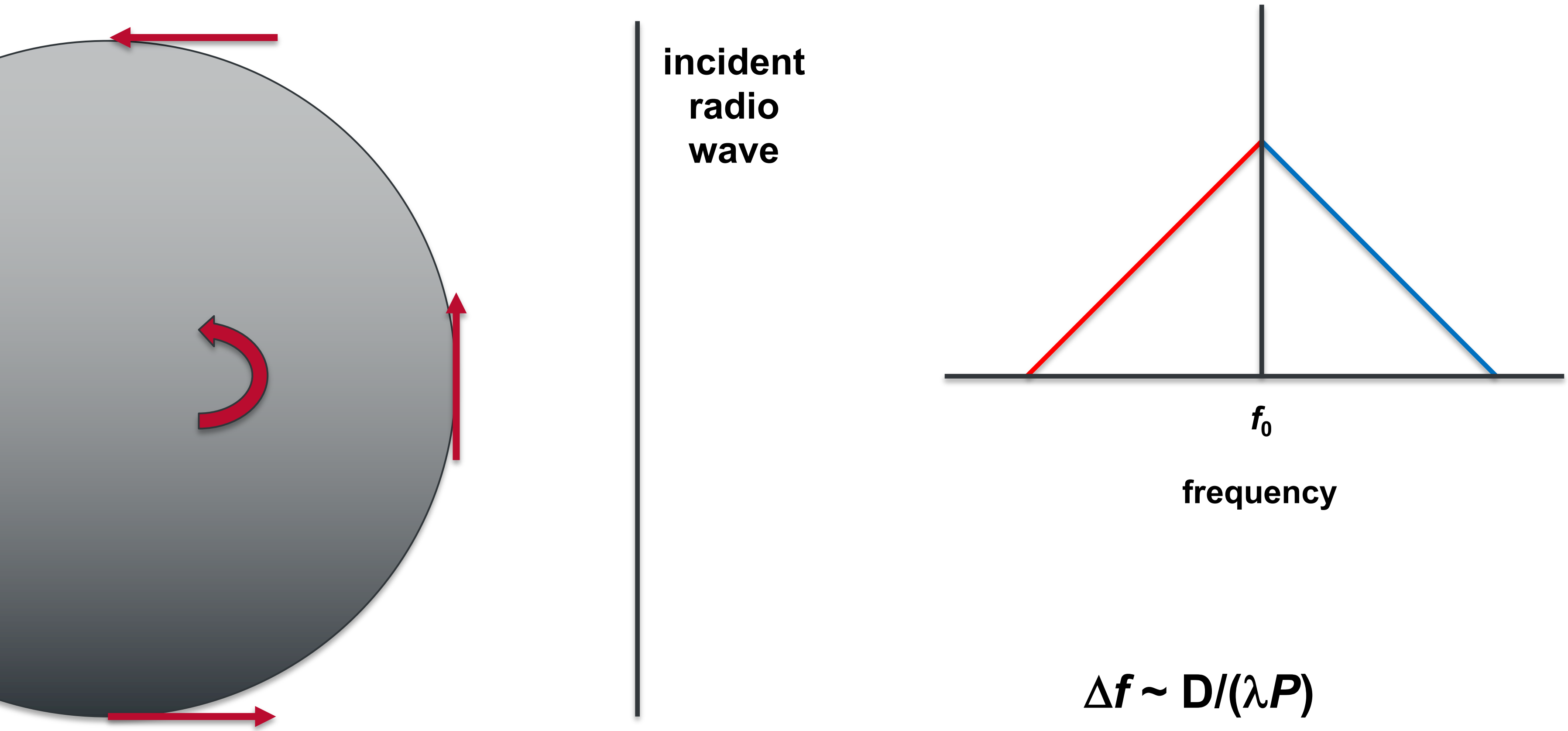
Linear Frequency Modulation ("chirp")

Constant amplitude, linear frequency ramp



Continuous Wave

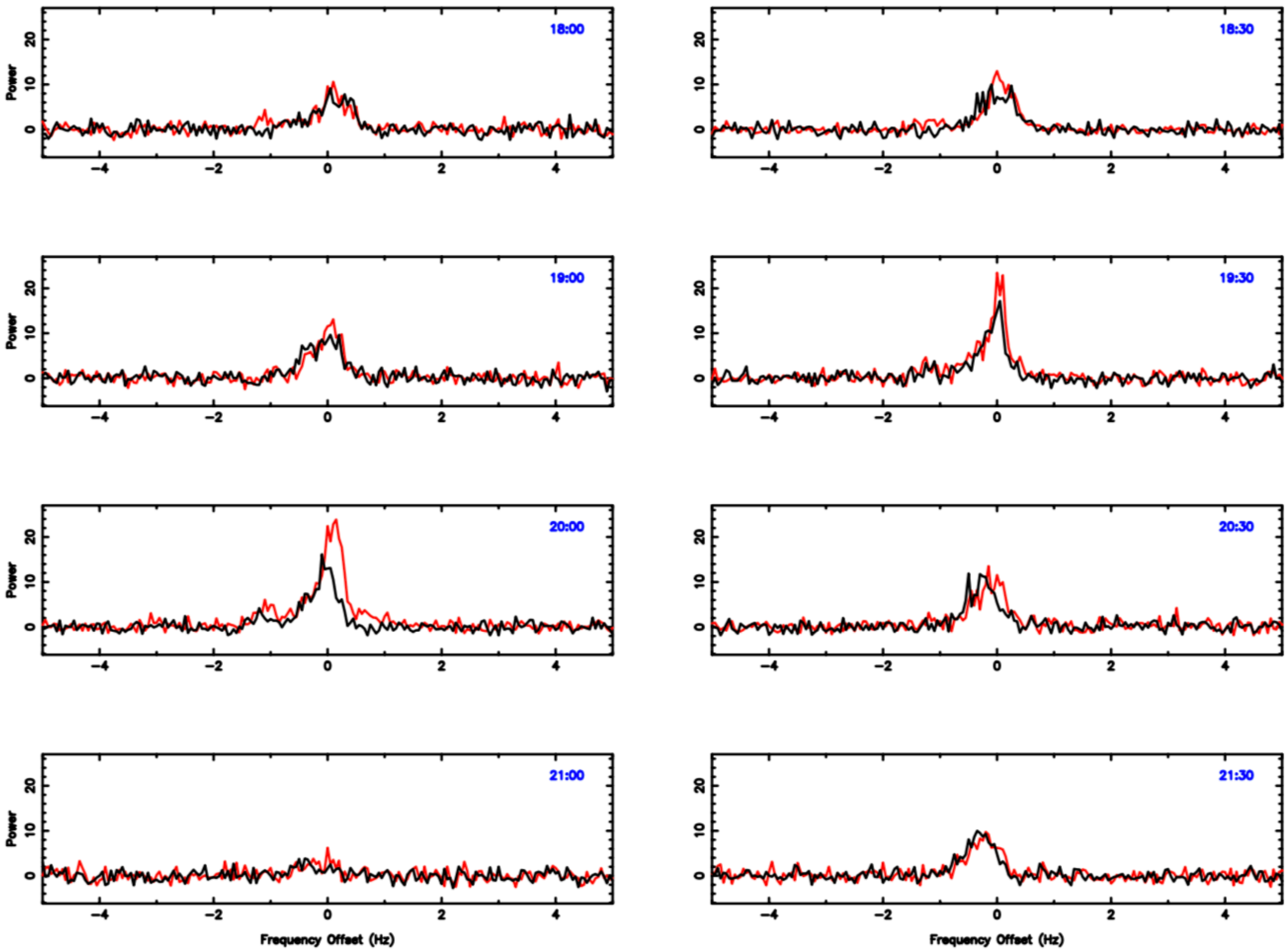
Radar Signal Processing



$$\Delta f \sim D/(\lambda P)$$

Continuous Wave

Radar Signal Processing

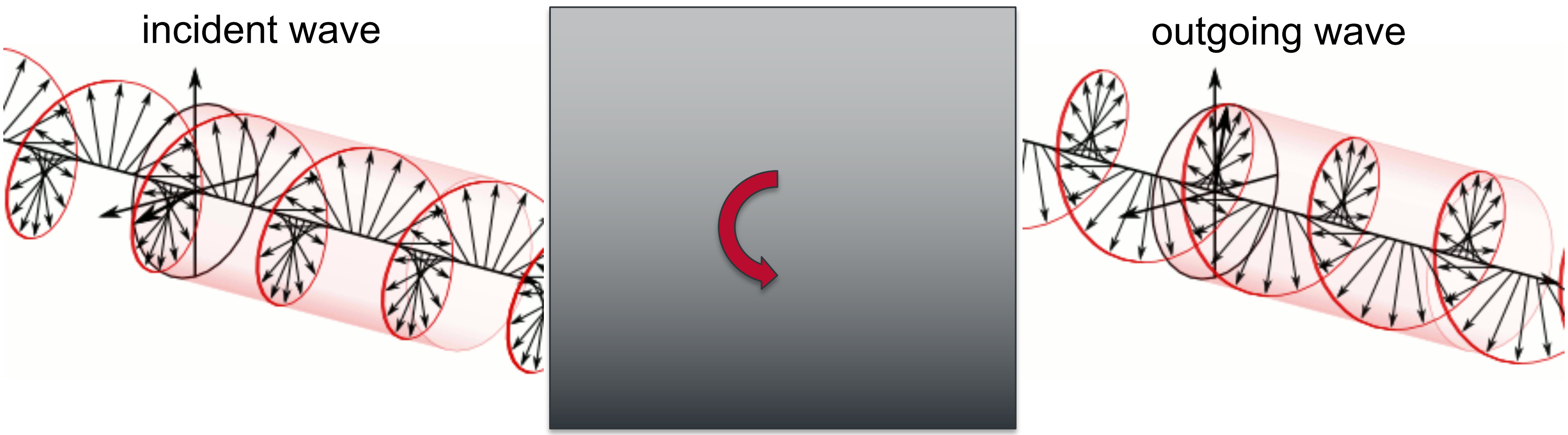


2005 UL5 2015 November 19 DSS-43--Parkes

Benson et al.

Continuous Wave

Radar Signal Processing



Credit: Dave3457

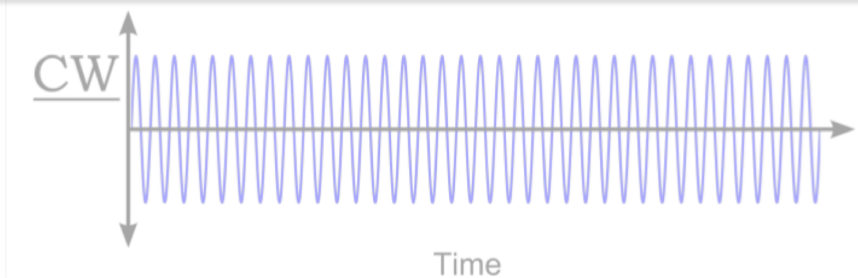
Expect "opposite sense" circular polarization (OC)

Can receive "same sense circular polarization

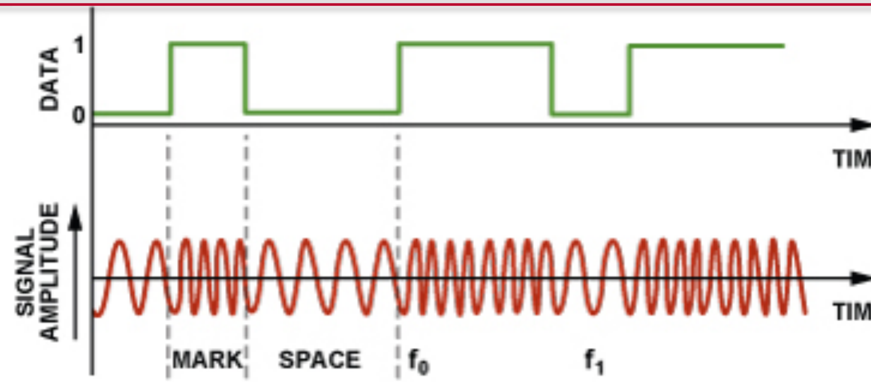
Ratio of OC/SC provides surface characterization

Radar Signal Processing

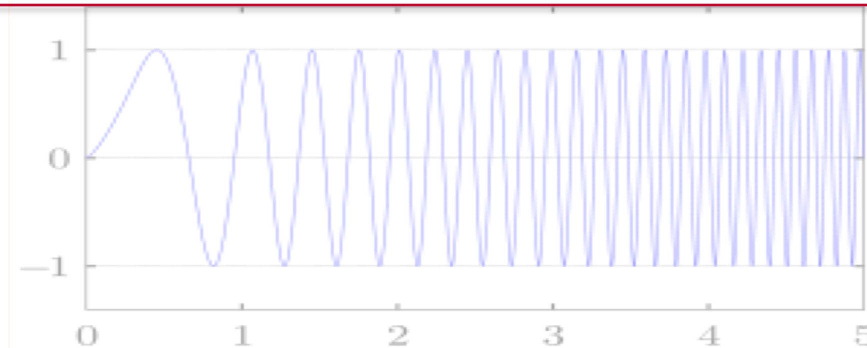
Continuous Wave
Circularly polarized radio wave with constant amplitude and frequency



Binary Phase Coding (BPC)
Time-encode waveform

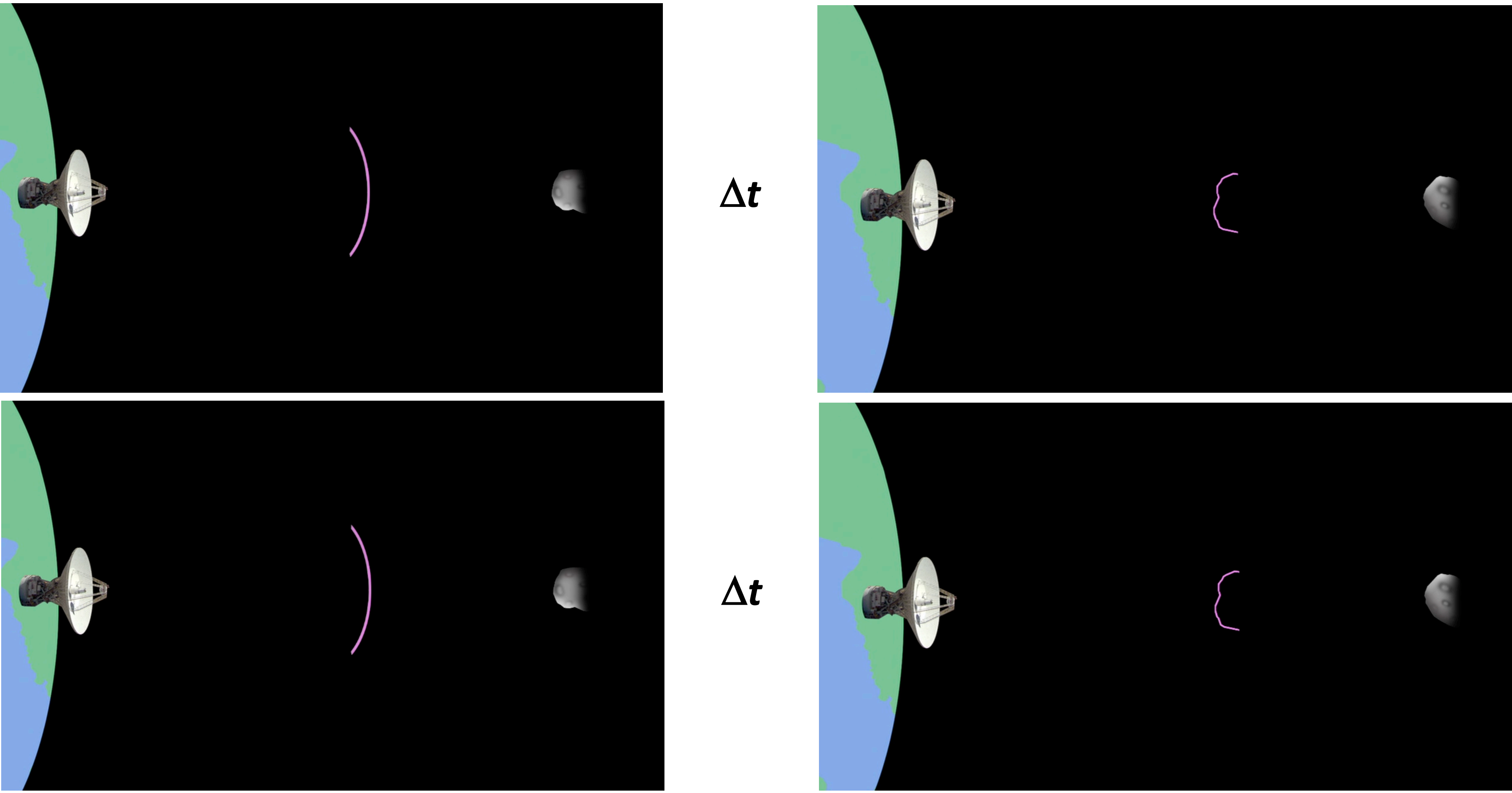


Linear Frequency Modulation ("chirp")
Constant amplitude, linear frequency ramp



Ranging

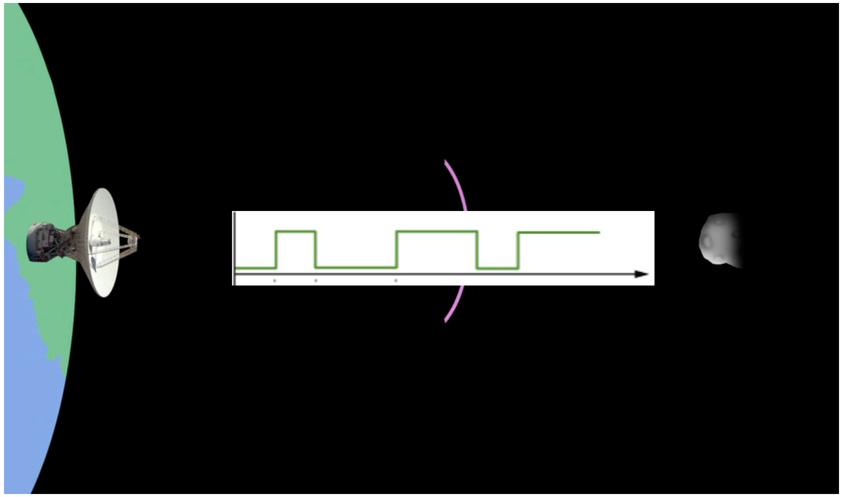
Radar Signal Processing

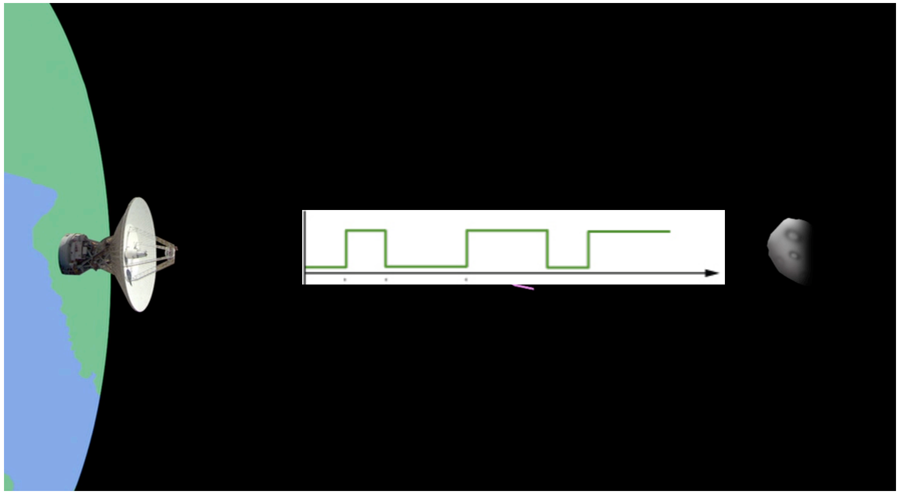


…

Ranging

Radar Signal Processing



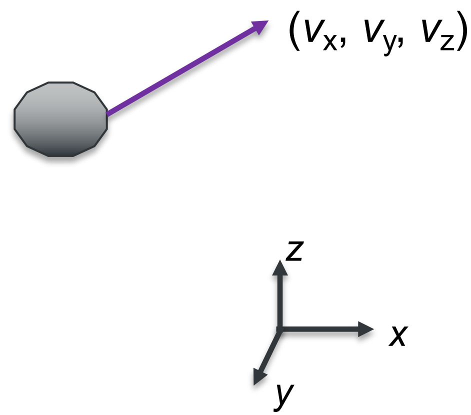


Key parameter: spacing of pulses, dependent upon S/N ratio

GSSR: 10 μs, 3 μs, 1 μs, …

Orbit Determination Improvements with Radar

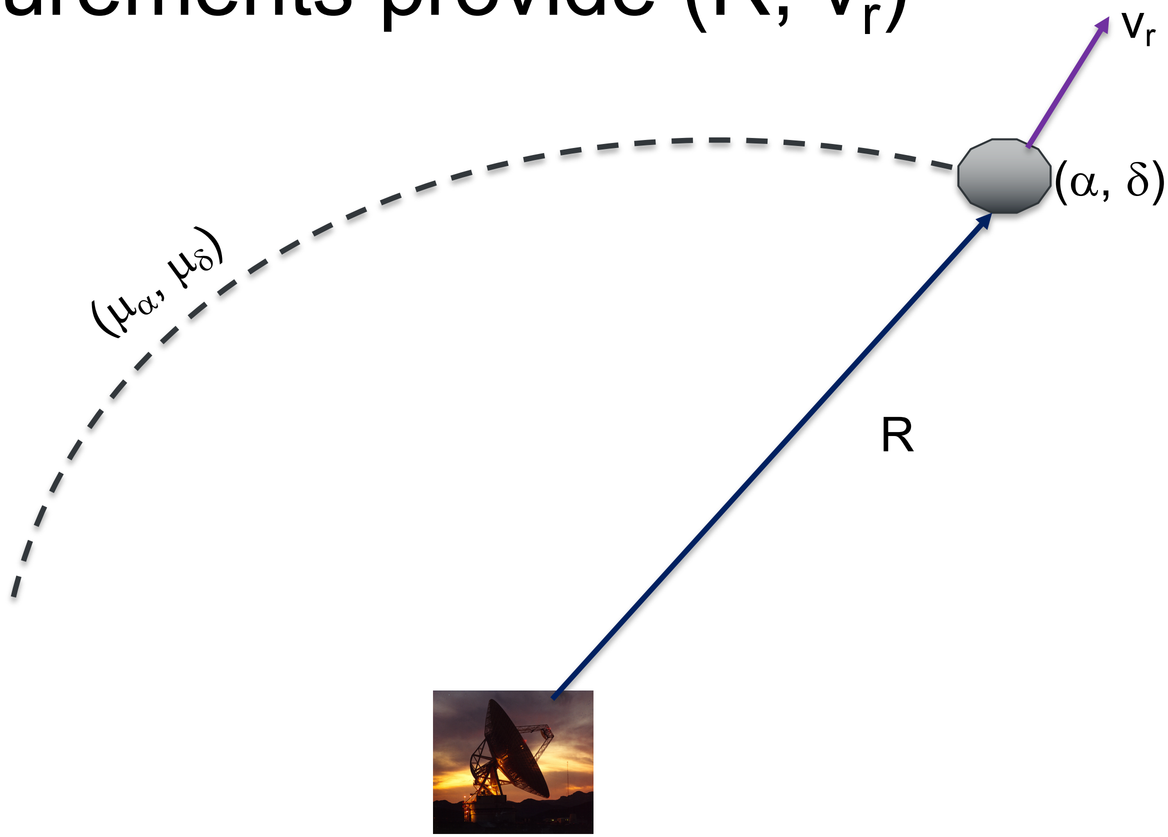
Would like (x, y, z; v_x, v_y, v_z)



Orbit Determination Improvements with Radar

Optical measurements provide (α, δ; μ_α, μ_δ)

Radar measurements provide (R, v_r)



Orbit Determination Improvements with Radar

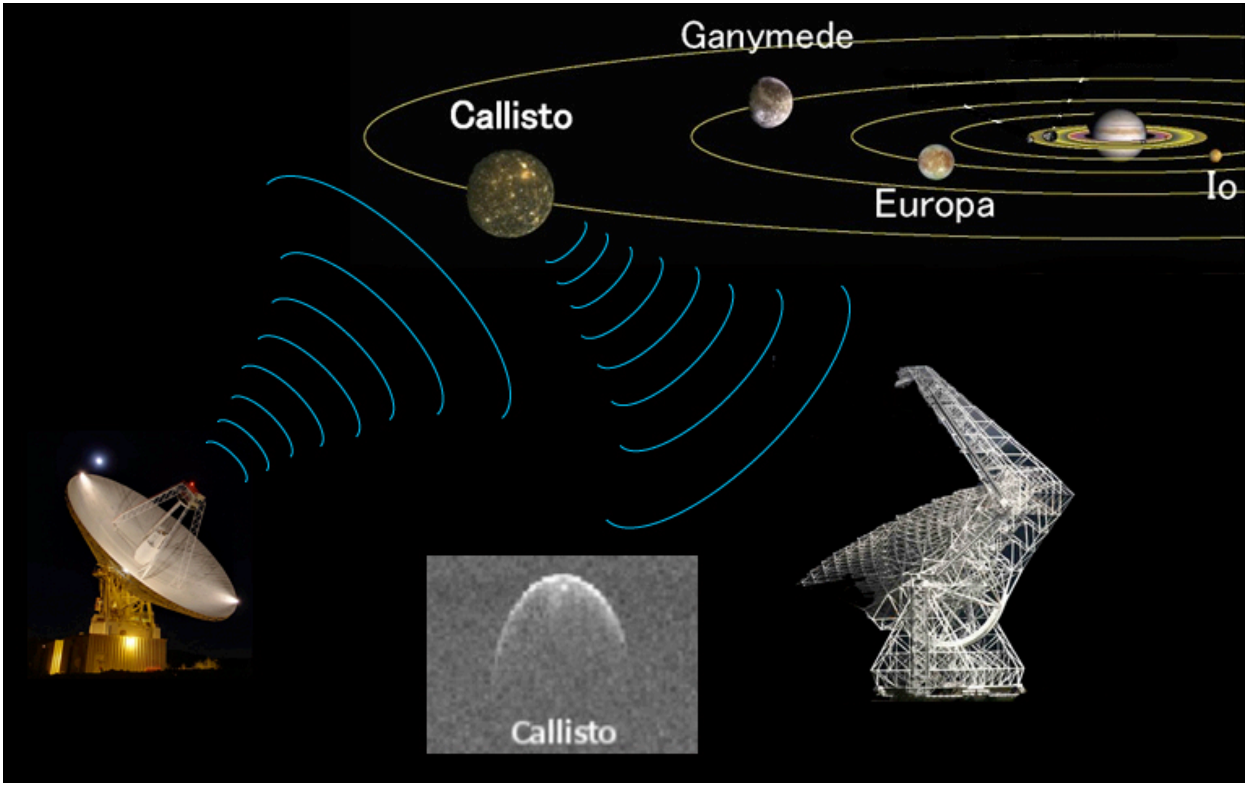
Radar delay-Doppler measurements

- Time delay to 8 m (150 m--300 m typical)
- Doppler (a.k.a. range-rate) to 1.6 mm/s (8 mm/s typical)

For Potentially Hazardous Asteroids, historical average prediction extent is …

- 1st apparition: +80 years without radar, +400 years with radar
  - ➢ Radar extends prediction window at discovery ~ 5x
  - ➢ Reduces orbit uncertainties ~ 10^5 (at discovery)
- 2nd apparition: +800 years with or w/o radar, but cuts uncertainties 50%

Ranging to the Galilean Satellites



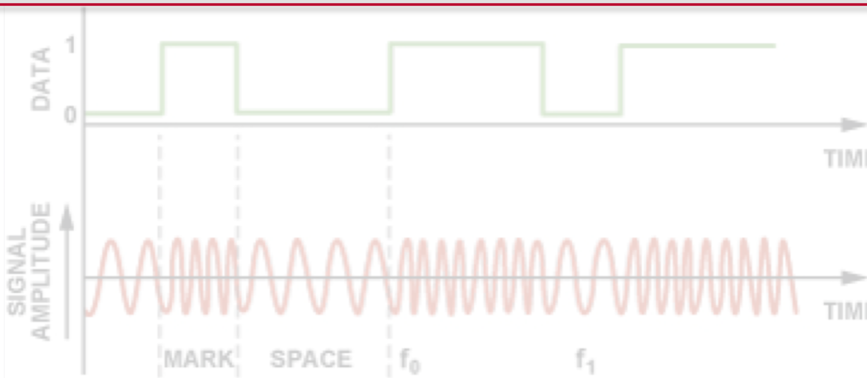
Jupiter's tidal dissipation constrains interior structure

- GSSR, Arecibo, GBT ranging to Galilean satellites
  Aiming for 2 km uncertainties in orbits (5× improvement)
- Detect secular acceleration of Galilean satellites from Jovian tides
  - Determine tidal dissipation parameter k_2/Q
  - Juno measures k_2

Radar Signal Processing

Continuous Wave
Circularly polarized radio wave with constant amplitude and frequency

Binary Phase Coding (BPC)
Time-encode waveform



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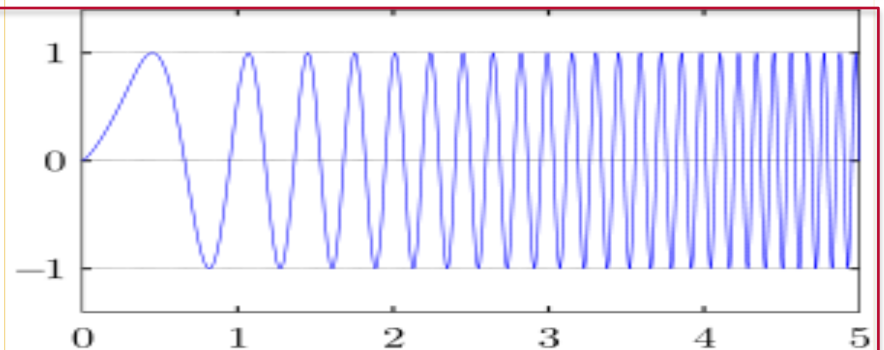
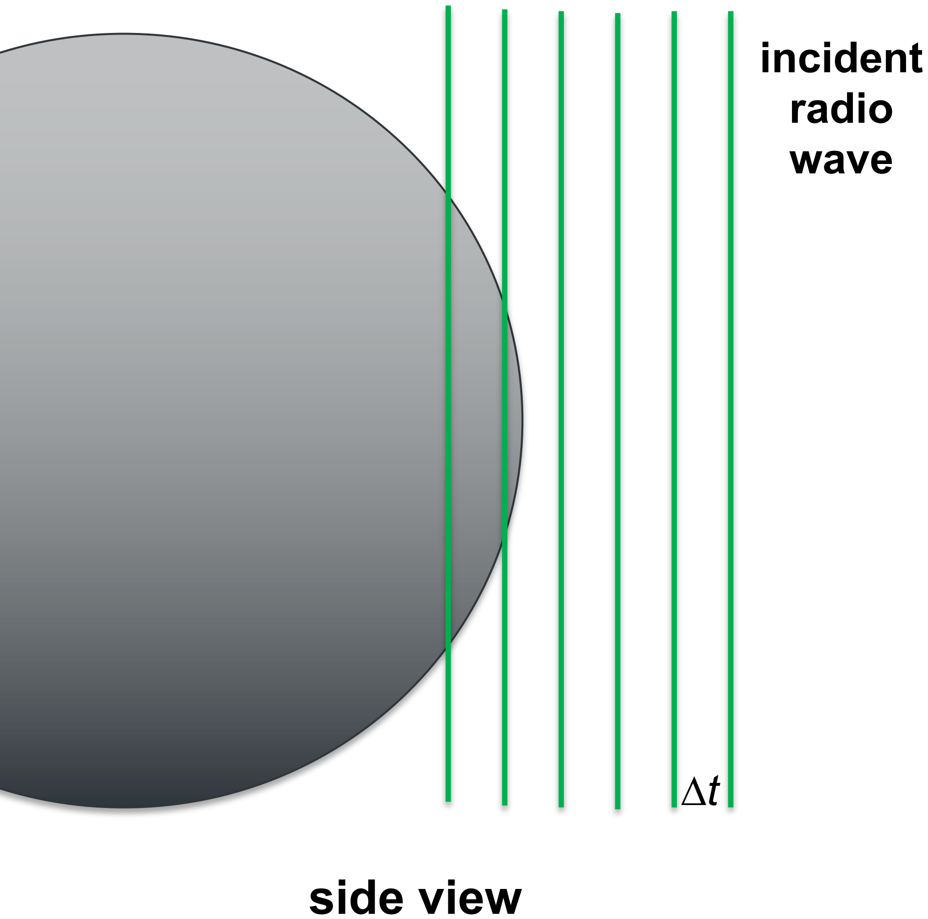
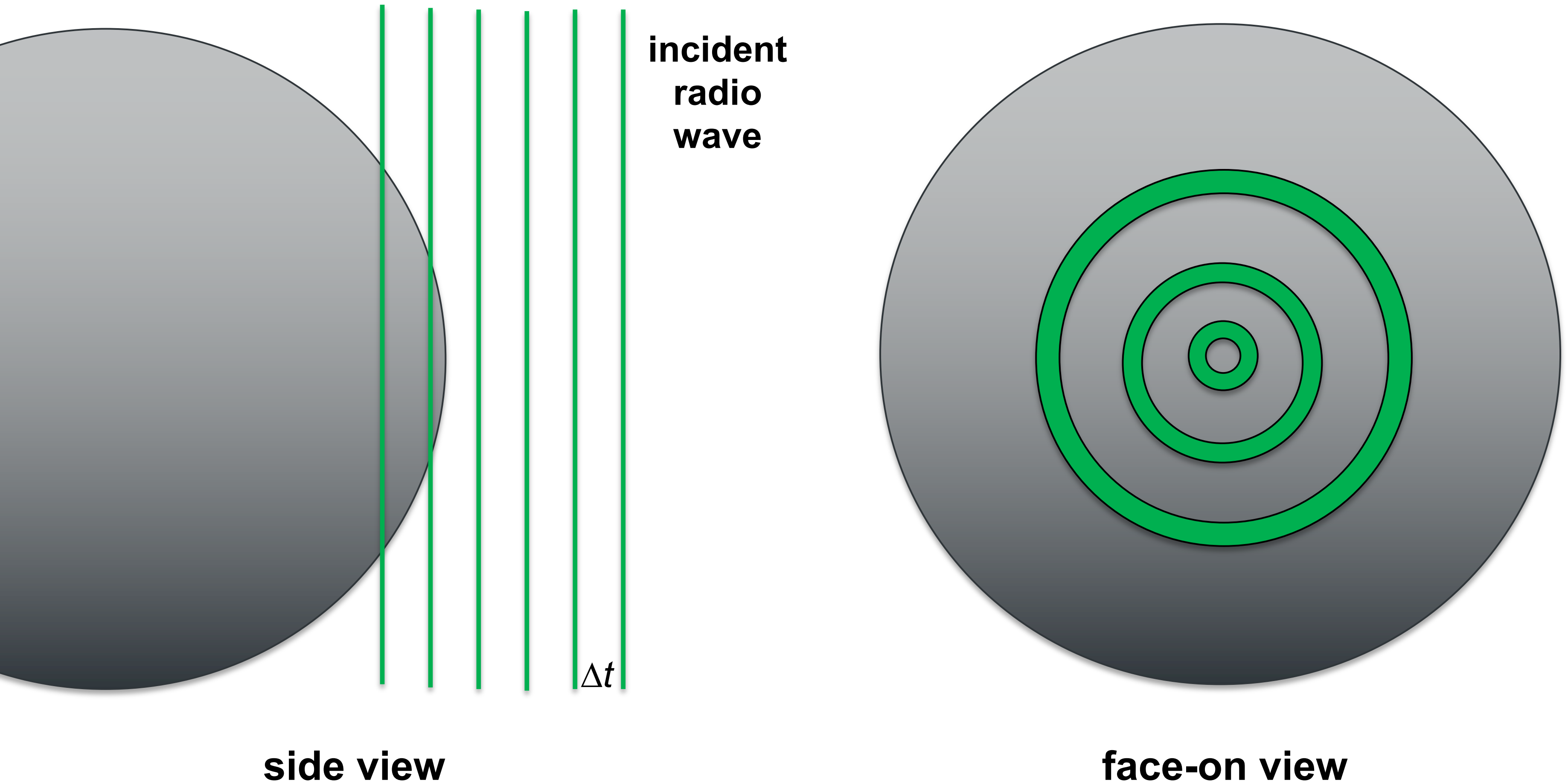
Constant amplitude, linear frequency ramp



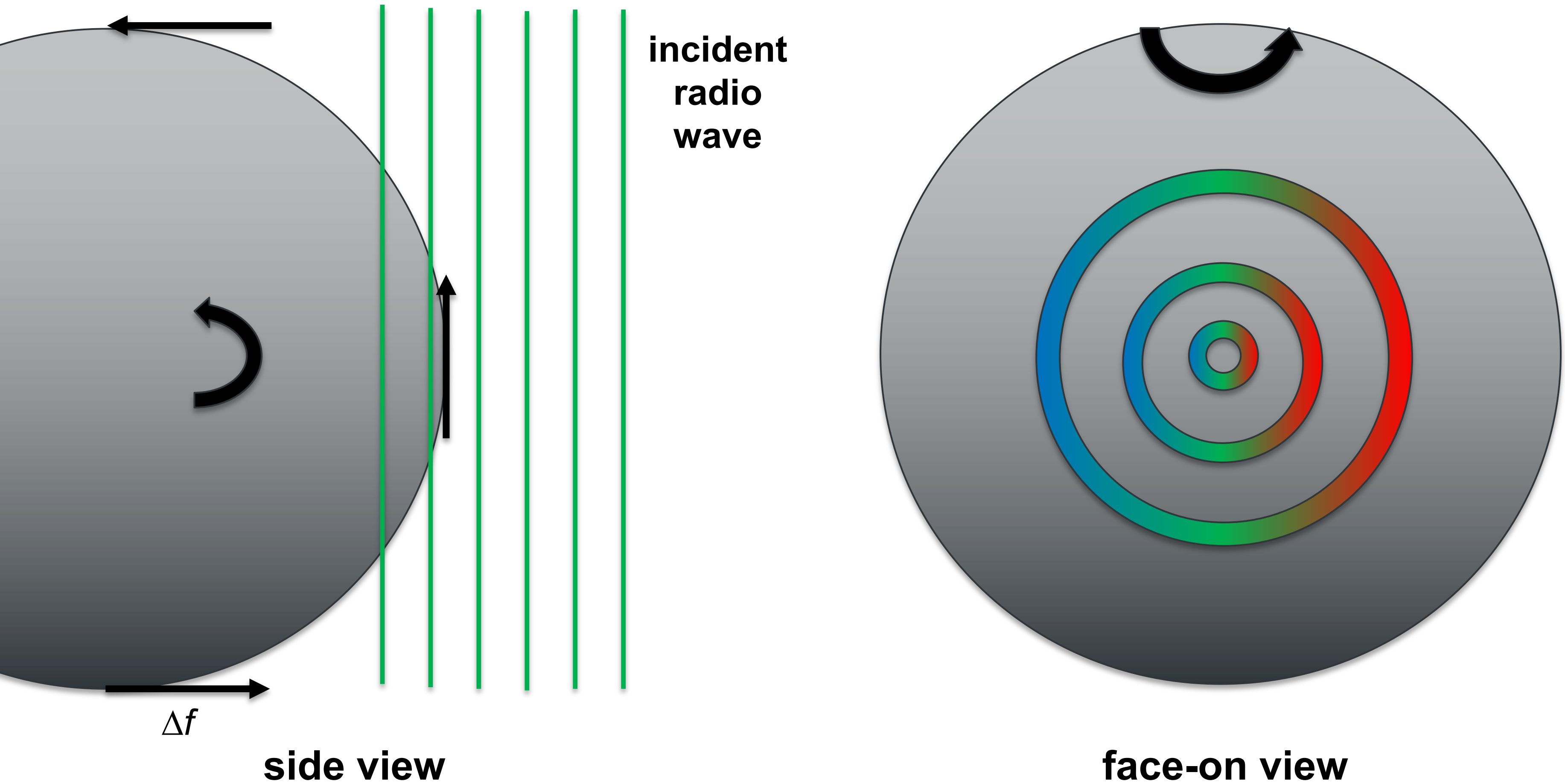
Linear Phase Modulation---Delay-Doppler Imaging



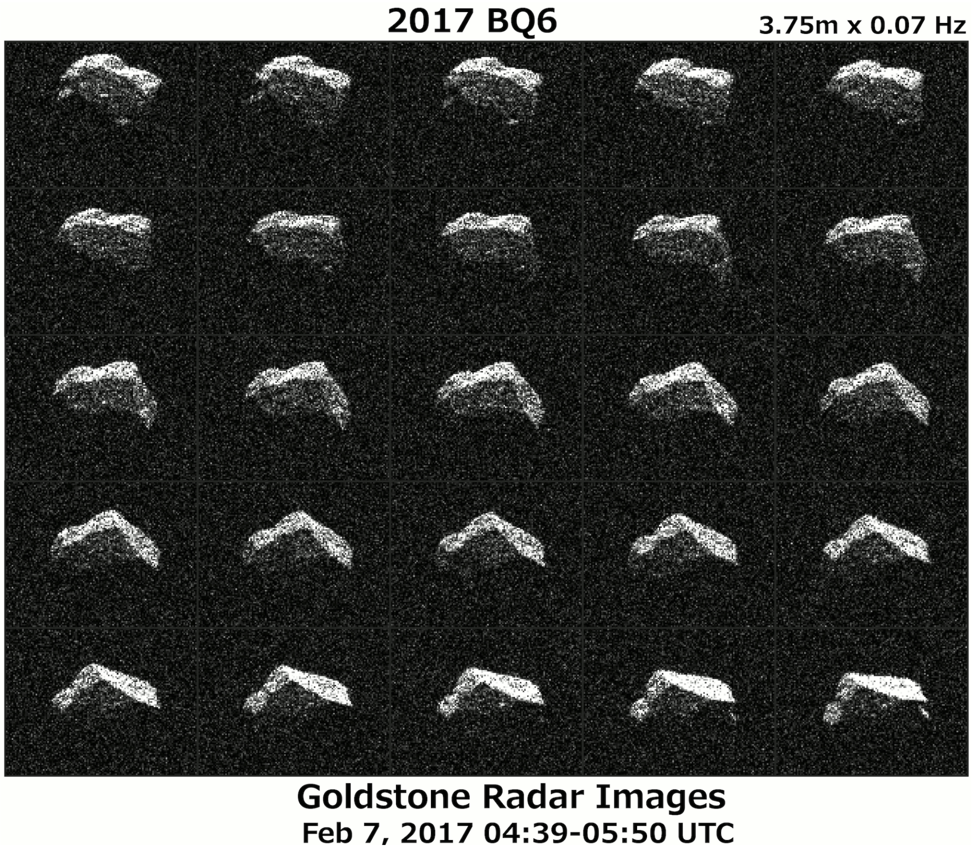
Linear Phase Modulation---Delay-Doppler Imaging

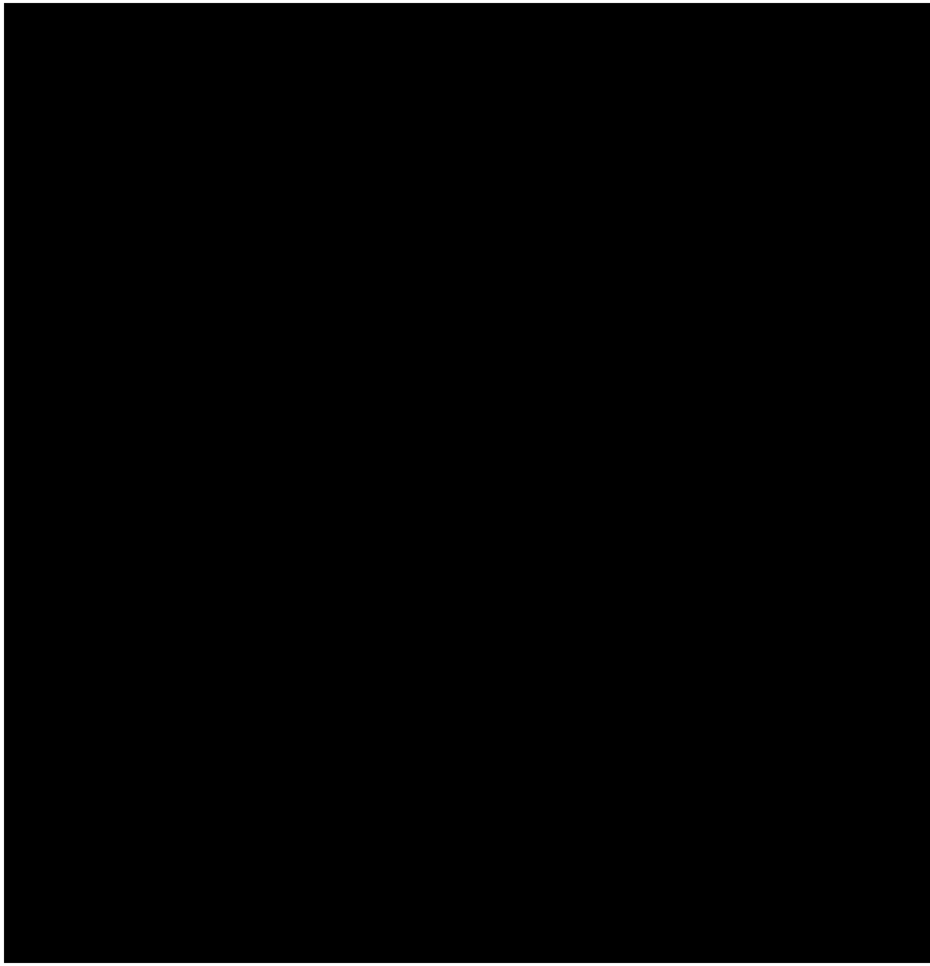


Linear Phase Modulation---Delay-Doppler Imaging



Delay-Doppler Imaging



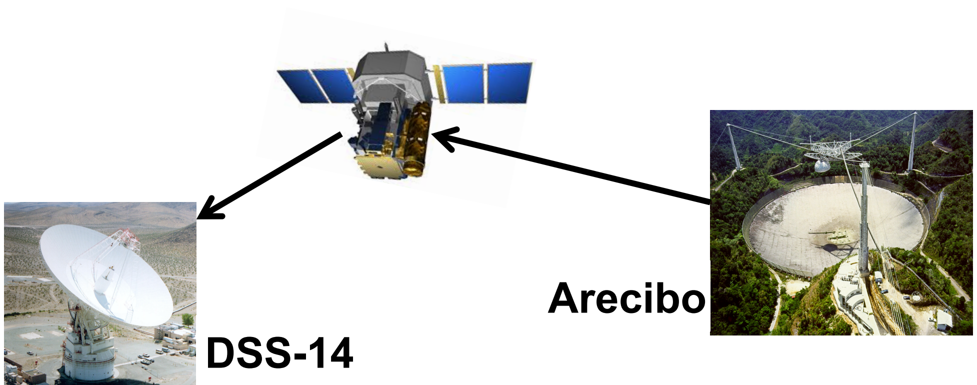


Finding Lost Spacecraft

Solar & Heliophysics Observatory (SOHO)

Joint ESA-NASA mission

- **Launched 1995 December**
- **Earth−Sun L1 (~ 4 lunar distances)**
- **Width with solar array 9.5 m**
- **Lost contact 1998 June**
- **Found 1998 July with Arecibo + DSS-14**

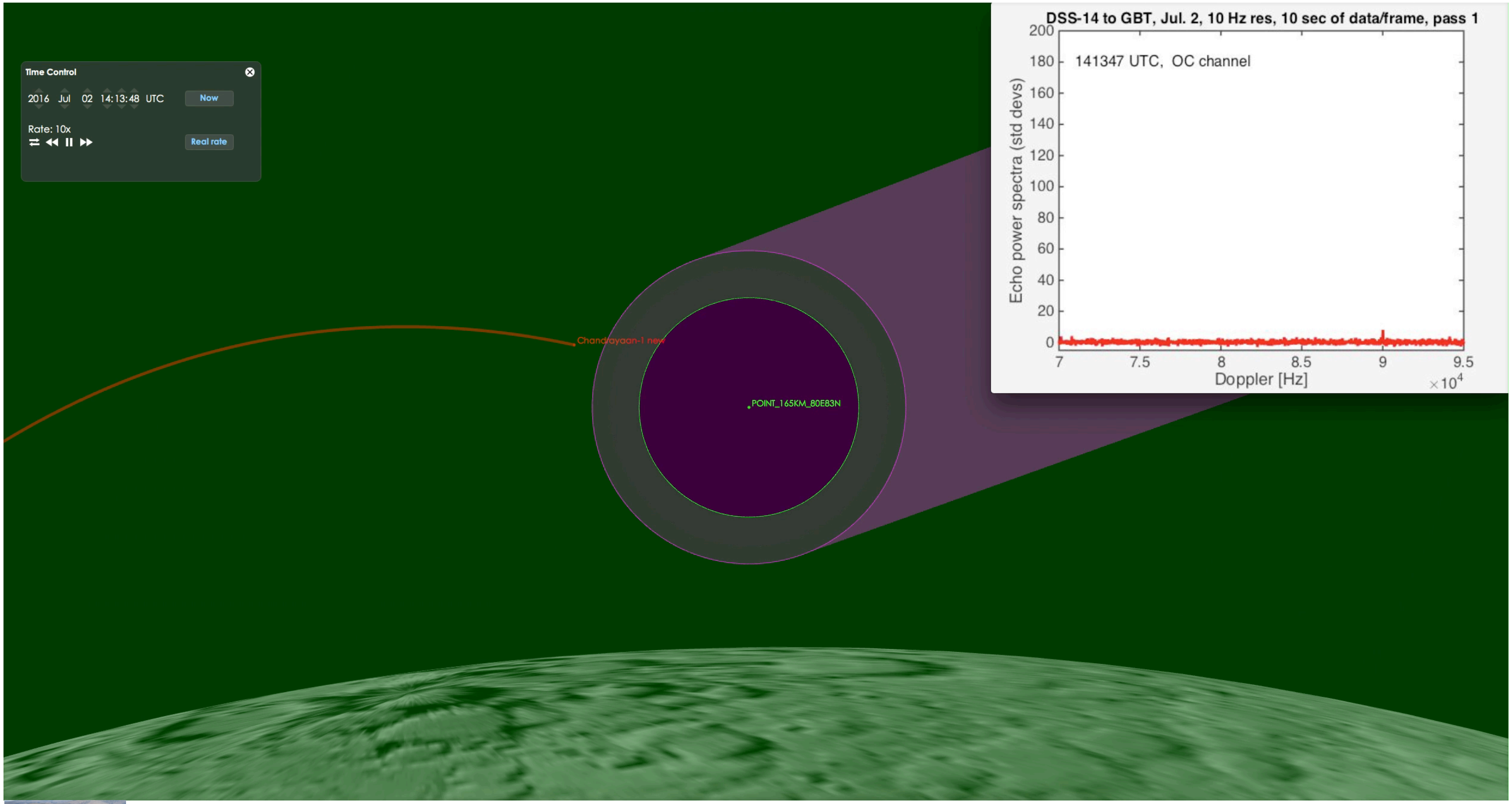


https://science.nasa.gov/science-news/science-at-nasa/1998/ast28jul98_1

SOHO spacecraft

Radar Recovery of Chandrayaan-1

Lunar Orbiting Spacecraft



DSS-14

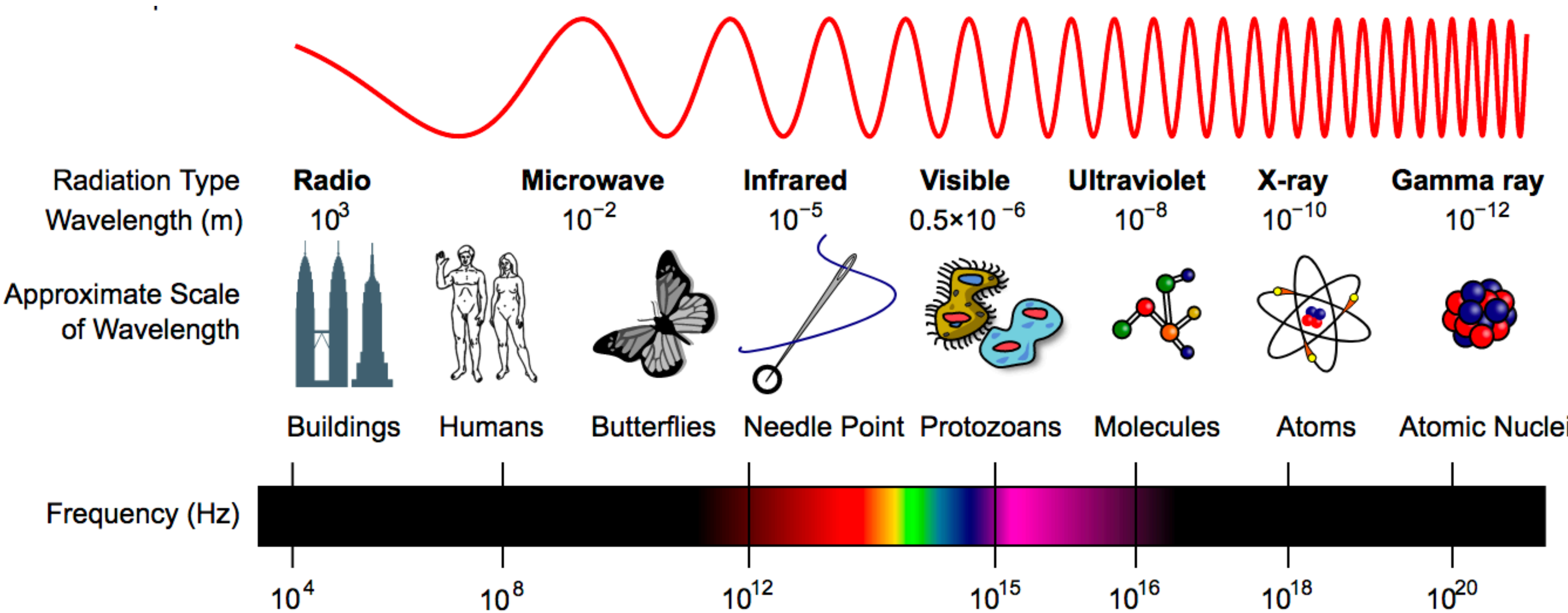
GBT

Radar Astronomy

Summary

- Long history of using deep space antennas for planetary radar due to their large sizes and transmitters
  - Ranging and orbit determination
  - Surface characterization
  - Rotation
  - …
- Radar equation drives many requirements ($1/R^4$)

Electromagnetic Spectrum



Credit:
Wikipedia Images